

COMMUNICATIONS SERIES — PART I

COMMUNICATION SYSTEM TRANSMISSION LOSSES

Prepared by:

Jim Bainter

Applications Engineering

This report shows the derivation of the equations used to calculate the insertion loss associated with various component parts of a communications channel. The combinations of components form a system whose overall loss may not be equal to the sum of the losses of the various parts.



MOTOROLA Semiconductor Products Inc.

COMMUNICATION SYSTEM TRANSMISSION LOSSES

INTRODUCTION

In the analysis of various component parts of a communication channel, resistive or reactive elements in series or shunt with the transmission path can introduce losses.

It is frequently necessary to calculate the magnitude of these losses, and the limit values of the components responsible for the losses in order to keep those losses within design goals.

For example, suppose an electronic crosspoint switch is inserted into the communications channel which has an "ON" resistance of 10-ohms. What is the insertion loss caused by this electronic switch?

Equations for computing these losses are derived in this paper. Further, computer generated tables are given for series resistance, reactance and parallel resistance, reactance for various system impedances.

INSERTION LOSS

Insertion loss is the ratio of power delivered to the load before and after the component in question is inserted into the communications channel expressed in decibels. The power delivered to the load, without the component in question inserted, is considered to be the maximum available power from the source. That is the source and load have matched impedances.

Figure 1 shows a signal source connected to a load in which the source and load resistance are matched or equal.

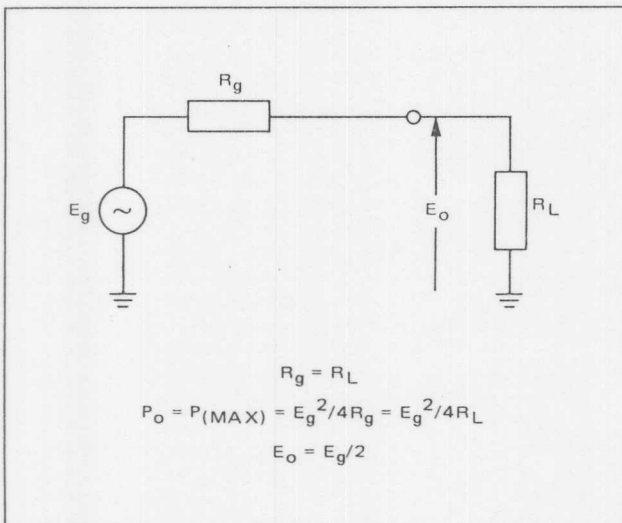


FIGURE 1

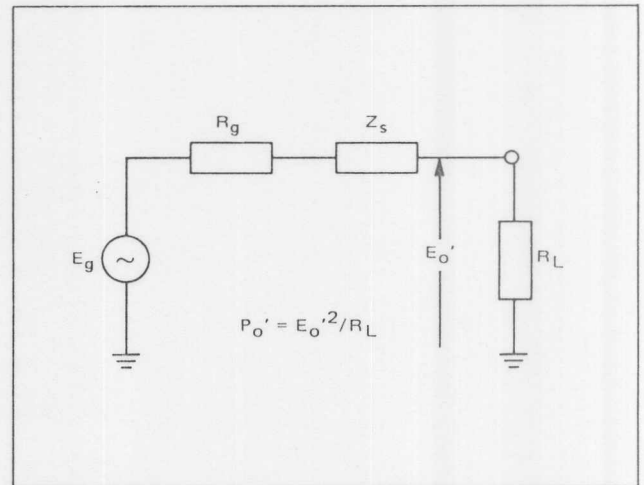


FIGURE 2

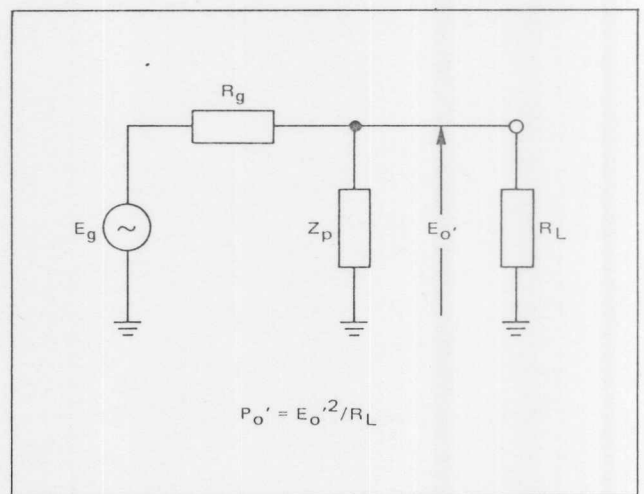


FIGURE 3

This is the condition for maximum transfer of power from the signal source to the load impedance R_L . This maximum available power $P(\text{MAX})$ is the reference power used for calculating the insertion loss of any component inserted in the path between the source and load as shown in Figures 2 and 3.

In the following sections the insertion loss question will be handled in four sections:

1. Insertion of Series Resistance.
2. Insertion of Series Reactance.
3. Insertion of Parallel Resistance.
4. Insertion of Parallel Reactance.

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INSERTION LOSS OF SERIES RESISTANCE

In Figure 2, if we let $Z_s = R$ the current in the load is:

$$I_L = \frac{E_g}{R_g + R + R_L} \text{ and since } R_g = R_L \quad (1)$$

$$I_L = \frac{E_g}{2R_L + R} \quad (2)$$

$$E'_O = R_L I_L = \frac{R_L E_g}{2R_L + R} \quad (3)$$

$$P'_O = \frac{E'^2_O}{R_L} = \frac{R_L E_g^2}{(2R_L + R)^2} \quad (4)$$

The insertion loss α in dB is defined as:

$$\alpha = 10 \log \frac{P(\text{MAX})}{P'_O} \quad (5)$$

$$\alpha = 10 \log \frac{E_g^2/4R_L}{R_L E_g^2/(2R_L + R)^2} \quad (6)$$

$$\alpha = 10 \log \frac{(2R_L + R)^2}{4R_L^2} \quad (7)$$

$$\alpha = 10 \log (1 + R/2R_L)^2 \quad (8)$$

$$\alpha = 20 \log (1 + R/2R_L) \text{ dB} \quad (9)$$

This equation can be used for example to find the insertion loss of a semiconductor switch. Assume the ON resistance of the semiconductor is 10-ohms, and it is inserted in a 600-ohm system. By using the above equation, the loss caused by the semiconductor would be 0.072-dB.

Another example would be where you want to know how much insertion loss is caused by the copper resistance in a transformer. Assume a 1:1 transformer as shown in Figure 4 is inserted in a 600-ohm system. Each winding has 30-ohms resistance. What is the insertion loss due to copper loss? Both the load and secondary resistance are transformed over to the primary by turns ratio squared

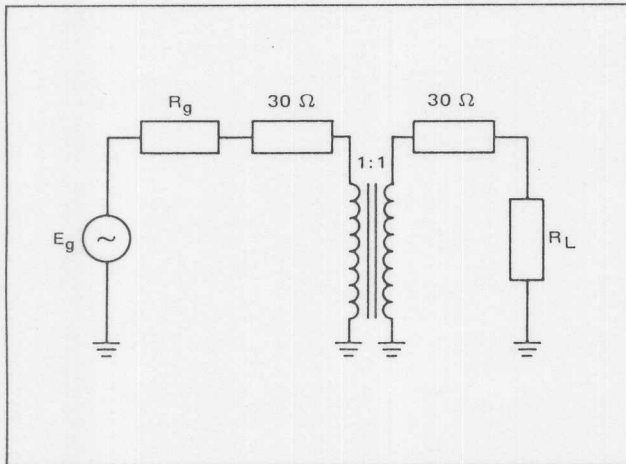


FIGURE 4

which in our example is one. The $R/2R_L$ ratio is then 60/1200 and the insertion loss is calculated to be 0.424-dB.

Table 1 is a printout showing various series inserted resistances and the resulting insertion losses with various system impedances.

TABLE I
System or Channel Impedance
Loss In (dB)

Series Resistance	50 Ohm	75 Ohm	135 Ohm	300 Ohm	600 Ohm	900 Ohm
1	0.086	0.058	0.032	0.014	0.007	0.006
2	0.172	0.115	0.064	0.029	0.014	0.010
3	0.257	0.172	0.096	0.043	0.022	0.014
4	0.341	0.229	0.128	0.058	0.029	0.019
5	0.424	0.285	0.159	0.072	0.036	0.024
6	0.506	0.341	0.191	0.086	0.043	0.029
7	0.588	0.396	0.222	0.101	0.051	0.034
8	0.668	0.451	0.254	0.115	0.058	0.039
9	0.749	0.506	0.285	0.129	0.065	0.043
10	0.828	0.561	0.316	0.144	0.072	0.048
12	0.984	0.668	0.378	0.172	0.086	0.058
14	1.138	0.775	0.439	0.200	0.101	0.067
16	1.289	0.880	0.500	0.229	0.115	0.077
18	1.438	0.984	0.561	0.257	0.129	0.086
20	1.584	1.087	0.621	0.285	0.144	0.096
25	1.938	1.339	0.769	0.355	0.179	0.120
30	2.279	1.584	0.915	0.424	0.214	0.144
35	2.607	1.822	1.059	0.492	0.250	0.167
40	2.923	2.053	1.200	0.561	0.285	0.191
45	3.227	2.279	1.339	0.628	0.320	0.214
50	3.522	2.499	1.476	0.695	0.355	0.238
60	4.082	2.923	1.743	0.828	0.424	0.285
70	4.609	3.327	2.002	0.958	0.492	0.331
80	5.105	3.713	2.254	1.087	0.561	0.378
90	5.575	4.082	2.499	1.214	0.628	0.424
100	6.021	4.437	2.737	1.339	0.695	0.470
110	6.444	4.778	2.968	1.462	0.762	0.515
120	6.848	5.105	3.194	1.584	0.828	0.561
130	7.235	5.421	3.414	1.703	0.893	0.606
140	7.604	5.726	3.628	1.822	0.958	0.651
150	7.959	6.021	3.838	1.938	1.023	0.695
160	8.299	6.305	4.042	2.053	1.087	0.740
170	8.627	6.581	4.242	2.167	1.151	0.784
180	8.943	6.848	4.437	2.279	1.214	0.828
190	9.248	7.108	4.628	2.390	1.277	0.872
200	9.542	7.360	4.815	2.499	1.339	0.915
250	10.881	8.519	5.693	3.025	1.644	1.130
300	12.041	9.542	6.490	3.522	1.938	1.339
350	13.064	10.458	7.221	3.911	2.223	1.543
400	13.979	11.285	7.894	4.437	2.499	1.743
450	14.807	12.041	8.519	4.861	2.766	1.938
500	15.563	12.736	9.103	5.265	3.025	2.129

SERIES INSERTED REACTANCE

The derivation of the loss equation for series inserted reactance follows along the same lines as before with the substitution of reactance X_s for Z_s in Figure 2.

$$I_L = \frac{E_g}{R_g + R_L \pm jX_s} = \frac{E_g}{2R_L \pm jX_s} \text{ since } R_g = R_L \quad (10)$$

$$E'_O = I_L R_L = \frac{E_g R_L}{2R_L \pm jX_s} = \frac{E_g R_L}{\sqrt{4R_L^2 + X_s^2}} \quad (11)$$

$$P'_O = \frac{E'^2_O}{R_L} = \frac{E_g^2 R_L}{4R_L^2 + X_s^2} \quad (12)$$

$$\frac{P(\text{MA})}{P'_O} = \frac{E_g^2/4R_L}{E_g^2 R_L / (4R_L^2 + X_s^2)} = \quad (13)$$

$$\frac{4R_L^2 + X_s^2}{4R_L^2} = 1 + \frac{1}{4} \left(\frac{X_s}{R_L} \right)^2$$

$$\therefore \alpha = 10 \log \left[1 + \frac{1}{4} \left(\frac{X_s}{R_L} \right)^2 \right] \text{ dB} \quad (14)$$

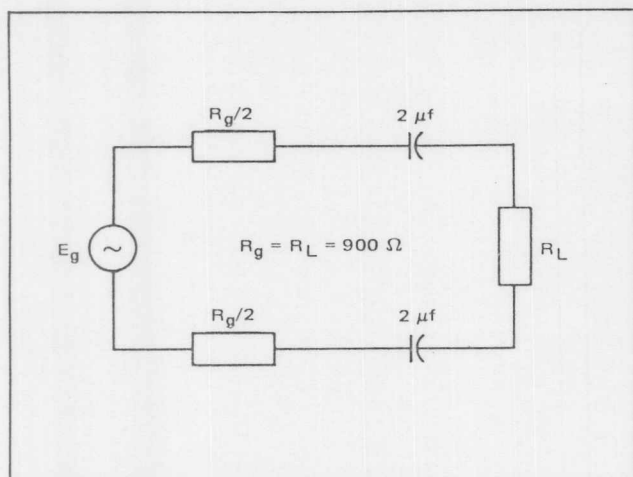


FIGURE 5

As an example of the use of equation 14, assume the impedance of the communications channel is 900-ohms and we have a balanced two wire channel with a 2 μf capacitor in series with each side of the line as shown in Figure 5. The equivalent unbalanced single wire circuit is shown in Figure 6. The value of capacitance used to calculate the loss is C/2. To calculate the loss at 300 Hz.

$$X_c = \frac{159.155 \text{ K}\Omega/\mu\text{f} \cdot \text{Hz}}{1 \mu\text{f} \times 300 \text{ Hz}} = 530.52 \Omega \quad (15)$$

$$\alpha = 10 \log \left[1 + \frac{1}{4} \left(\frac{530.5}{900} \right)^2 \right] \quad (16)$$

$$\alpha = 10 \log 1.08686 = 0.362 \text{ dB} \quad (17)$$

Table II is a printout of insertion loss for various series reactances with various system impedances.

PARALLEL INSERTED RESISTANCE

The derivation of the loss equation for parallel inserted resistance is as follows:

Figure 7 is the equivalent circuit used for this derivation.

$$I_L = I_g - I_p \quad (18)$$

$$\frac{E'_O}{R_L} = \frac{E_g - E'_O}{R_g} - \frac{E'_O}{R_p} \quad (19)$$

$$E'_O \left(\frac{1}{R_L} + \frac{1}{R_g} + \frac{1}{R_p} \right) = E_g/R_g \quad (20)$$

$$E'_O = \frac{E_g/R_L}{2/R_L + 1/R_p} \text{ Since } R_L = R_g \quad (21)$$

$$P'_O = \frac{E'^2_O}{R_L} = \frac{(E_g/R_L)^2}{R_L (2/R_L + 1/R_p)^2} \quad (22)$$

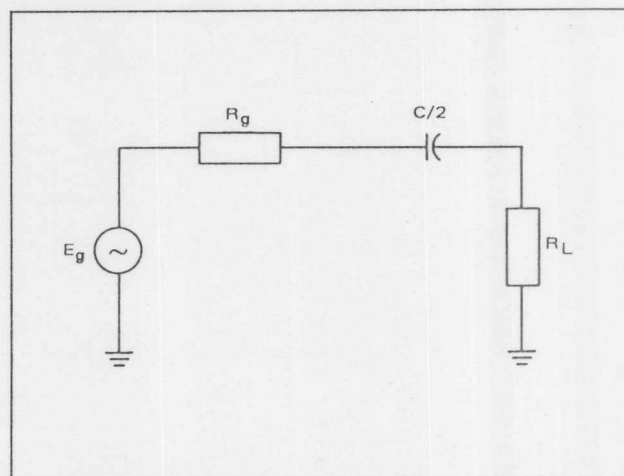


FIGURE 6

$$\frac{P_{(ma)}}{P'_O} = \frac{E_g^2/4R_L}{E_g^2/R_L (2 + R_L/R_p)^2} = (1 + R_L/2R_p)^2 \quad (23)$$

$$\therefore \alpha = 20 \log (1 + R_L/2R_p) \text{ dB} \quad (24)$$

TABLE II
System or Channel Impedance
Loss in (dB)

Series Reactance	50 Ohm	75 Ohm	135 Ohm	300 Ohm	600 Ohm	900 Ohm
1	0.000	0.000	0.000	0.000	0.000	0.000
2	0.002	0.001	0.000	0.000	0.000	0.000
3	0.004	0.002	0.001	0.000	0.000	0.000
4	0.007	0.003	0.001	0.000	0.000	0.000
5	0.011	0.005	0.001	0.000	0.000	0.000
6	0.016	0.007	0.002	0.000	0.000	0.000
7	0.021	0.009	0.003	0.001	0.000	0.000
8	0.028	0.012	0.004	0.001	0.000	0.000
9	0.035	0.016	0.005	0.001	0.000	0.000
10	0.043	0.019	0.006	0.001	0.000	0.000
12	0.062	0.028	0.009	0.002	0.000	0.000
14	0.084	0.038	0.012	0.002	0.001	0.000
16	0.110	0.049	0.015	0.003	0.001	0.000
18	0.138	0.062	0.019	0.004	0.001	0.000
20	0.170	0.077	0.024	0.005	0.001	0.001
25	0.263	0.119	0.037	0.008	0.002	0.001
30	0.374	0.170	0.053	0.011	0.003	0.001
35	0.502	0.230	0.072	0.015	0.004	0.002
40	0.645	0.298	0.094	0.019	0.005	0.002
45	0.801	0.374	0.119	0.024	0.006	0.003
50	0.969	0.458	0.146	0.030	0.008	0.003
60	1.335	0.645	0.209	0.043	0.011	0.005
70	1.732	0.856	0.283	0.059	0.015	0.007
80	2.148	1.087	0.365	0.077	0.019	0.009
90	3.577	1.335	0.458	0.097	0.024	0.011
100	3.010	1.597	0.558	0.119	0.030	0.013
110	3.444	1.869	0.667	0.144	0.036	0.016
120	3.874	2.148	0.783	0.170	0.043	0.019
130	4.298	2.433	0.905	0.199	0.051	0.023
140	4.713	2.721	1.034	0.230	0.059	0.026
150	5.119	3.010	1.168	0.263	0.067	0.030
160	5.514	3.300	1.307	0.298	0.077	0.034
170	5.899	3.588	1.450	0.335	0.086	0.039
180	6.274	3.874	1.597	0.374	0.097	0.043
190	6.637	4.157	1.747	0.415	0.108	0.048
200	6.990	4.437	1.900	0.458	0.119	0.053
250	8.603	5.772	2.689	0.695	0.185	0.083
300	10.000	6.990	3.492	0.969	0.263	0.119
350	11.222	8.092	4.282	1.272	0.355	0.161
400	12.304	9.091	5.044	1.597	0.458	0.209
450	13.274	10.000	5.772	1.938	0.571	0.263
500	14.150	10.832	6.463	2.290	0.695	0.323

As an example of the usage of equation 24 let us assume the channel or system impedance is 900-ohms, and we want to find the insertion loss caused by bridging or paralleling a tone receiver across the channel as shown in Figure 8. The input impedance of the receiver is 20K-ohms resistive.

$$\alpha = 20 \log \left(1 + \frac{900}{40000} \right) = 20 \log 1.0225 \quad (25)$$

$$\alpha = 0.193 \text{ dB} \quad (26)$$

One would also use equation 24 to find the insertion loss due to the iron losses in a transformer. The iron losses can be represented by an equivalent parallel loss resistance.

Table III is a printout of insertion loss due to various shunt or parallel resistive losses for various system impedances.

PARALLEL INSERTED REACTANCE

Figure 7 will be used for this derivation by replacing R_p with X_p . By making this substitution in equation 21 the following results:

$$E_o' = \frac{E_g/R_L}{2/R_L \pm j\frac{1}{X_p}} = \frac{E_g/R_L}{\sqrt{(2/R_L)^2 + \left(\frac{1}{X_p}\right)^2}} \quad (27)$$

$$P_o' = \frac{E_o'^2}{R_L} = \frac{(E_g/R_L)^2}{R_L \left[(2/R_L)^2 + \left(\frac{1}{X_p}\right)^2 \right]} = \frac{E_g^2}{R_L \left[4 + \left(\frac{R_L}{X_p}\right)^2 \right]} \quad (28)$$

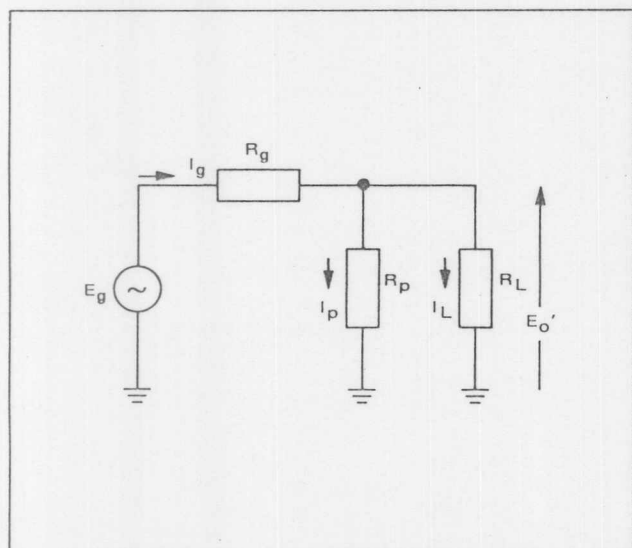


FIGURE 7

$$\frac{P_{(max)}}{P_o'} = \frac{E_g^2/4R_L}{E_g^2/R_L \left[4 + \left(\frac{R_L}{X_p}\right)^2 \right]} = 1 + \frac{1}{4} \left(\frac{R_L}{X_p}\right)^2 \quad (29)$$

$$\alpha = 10 \log \left[1 + \frac{1}{4} \left(\frac{R_L}{X_p}\right)^2 \right] \text{ dB} \quad (30)$$

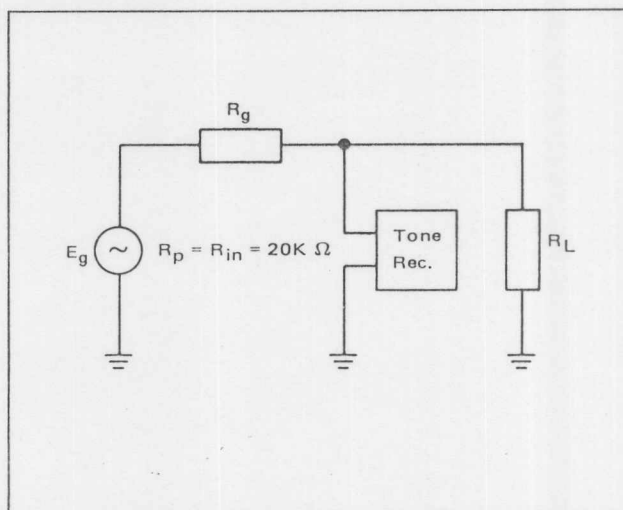


FIGURE 8

TABLE III
System or Channel Impedance
Loss In (dB)

Parallel Resistance (k Ohm)	50 Ohm	75 Ohm	135 Ohm	300 Ohm	600 Ohm	900 Ohm
0.1	1.938	2.766	4.480	7.959	12.041	14.807
0.2	1.023	1.493	2.526	4.861	7.959	10.238
0.3	0.695	1.023	1.763	3.522	6.021	7.959
0.4	0.527	0.778	1.354	2.766	4.861	6.547
0.5	0.424	0.628	1.100	2.279	4.082	5.575
0.6	0.355	0.527	0.926	1.938	3.522	4.861
0.7	0.305	0.453	0.800	1.686	3.098	4.312
0.8	0.267	0.398	0.704	1.493	2.766	3.876
0.9	0.238	0.355	0.628	1.339	2.499	3.522
1.0	0.214	0.320	0.567	1.214	2.279	3.227
1.2	0.179	0.267	0.475	1.023	1.938	2.766
1.4	0.154	0.230	0.409	0.884	1.686	2.421
1.6	0.135	0.201	0.359	0.778	1.493	2.153
1.8	0.120	0.179	0.320	0.695	1.339	1.938
2.0	0.108	0.161	0.288	0.628	1.214	1.763
2.5	0.086	0.129	0.231	0.506	0.984	1.438
3.0	0.072	0.108	0.193	0.424	0.828	1.214
3.5	0.062	0.093	0.166	0.364	0.714	1.051
4.0	0.054	0.081	0.145	0.320	0.628	0.926
4.5	0.048	0.072	0.129	0.285	0.561	0.828
5.0	0.043	0.065	0.116	0.257	0.506	0.749
6.0	0.036	0.054	0.097	0.214	0.424	0.628
7.0	0.031	0.046	0.083	0.184	0.364	0.541
8.0	0.027	0.041	0.073	0.161	0.320	0.475
9.0	0.024	0.036	0.065	0.144	0.285	0.424
10.0	0.022	0.033	0.058	0.129	0.257	0.382
11.0	0.020	0.030	0.053	0.118	0.234	0.348
12.0	0.018	0.027	0.049	0.108	0.214	0.320
13.0	0.017	0.025	0.045	0.100	0.198	0.296
14.0	0.015	0.023	0.042	0.093	0.184	0.275
15.0	0.014	0.022	0.039	0.086	0.172	0.257
16.0	0.014	0.020	0.037	0.081	0.161	0.241
17.0	0.013	0.019	0.034	0.076	0.152	0.227
18.0	0.012	0.018	0.033	0.072	0.144	0.214
19.0	0.011	0.017	0.031	0.068	0.136	0.203
20.0	0.011	0.016	0.029	0.065	0.129	0.193
25.0	0.009	0.013	0.023	0.052	0.104	0.155
30.0	0.007	0.011	0.020	0.043	0.086	0.129
35.0	0.006	0.009	0.017	0.037	0.074	0.111
40.0	0.005	0.008	0.015	0.033	0.065	0.097
45.0	0.005	0.007	0.013	0.029	0.058	0.086
50.0	0.004	0.007	0.012	0.026	0.052	0.078
60.0	0.004	0.005	0.010	0.022	0.043	0.065
70.0	0.003	0.005	0.008	0.019	0.037	0.056
80.0	0.003	0.004	0.007	0.016	0.033	0.049
90.0	0.002	0.004	0.007	0.014	0.029	0.043
100.0	0.002	0.003	0.006	0.013	0.026	0.039

Assume a semiconductor placed across a 50-ohm transmission channel and is biased off but has a 10pf capacitance. What is the insertion loss due to 10pf at 100-MHz?

$$X_c = \frac{159.155 \text{ K}\Omega/\mu\text{f} - \text{Hz}}{10\text{pf} \times 100 \text{ MHz}} = 0.159 \text{ K}\Omega \quad (31)$$

$$\alpha = 10 \log \left[1 + \frac{1}{4} \left(\frac{50}{159} \right)^2 \right] = 10 \log 1.0247 \quad (32)$$

$$\alpha = 0.106 \text{ dB} \quad (33)$$

Another example would be where it was desired to find the insertion loss component due to the reactance of transformer primary placed across a 900-ohm system. Assume the $X_p = 3000$ -ohms.

$$\alpha = 10 \log \left[1 + \frac{1}{4} \left(\frac{900}{3000} \right)^2 \right] = 10 \log 1.0225 \quad (34)$$

$$\alpha = 0.0966 \text{ dB} \quad (35)$$

Table IV is a listing of the various insertion losses with various parallel reactances and system impedances.

This paper has shown the derivation of the equations used to find the insertion loss associated with various component parts of a communications channel. When various combinations of components are together to form a system it will be found that the overall loss of the channel may not be equal to the sum of the insertion losses of the various parts since there is a loss due to mismatch which is beyond the scope of this paper. One will appreciate the fact though, that if one adds 10-ohms in a 600-ohm system one no longer has a 600-ohm system. If you add half of the 10-ohms to the source and half to the load, you now have a 605-ohm system.

TABLE IV
System or Channel Impedance
Loss In (dB)

Parallel Reactance (k Ohm)	50 Ohm	75 Ohm	135 Ohm	300 Ohm	600 Ohm	900 Ohm
0.1	0.263	0.571	1.630	5.119	10.000	13.274
0.2	0.067	0.150	0.468	1.938	5.119	7.827
0.3	0.030	0.067	0.214	0.969	3.010	5.119
0.4	0.017	0.038	0.122	0.571	1.938	3.552
0.5	0.011	0.024	0.078	0.374	1.335	2.577
0.6	0.008	0.017	0.055	0.263	0.969	1.938
0.7	0.006	0.012	0.040	0.195	0.732	1.502
0.8	0.004	0.010	0.031	0.150	0.571	1.194
0.9	0.003	0.008	0.024	0.119	0.458	0.969
1.0	0.003	0.006	0.020	0.097	0.374	0.801
1.2	0.002	0.004	0.014	0.067	0.263	0.571
1.4	0.001	0.003	0.010	0.050	0.195	0.427
1.6	0.001	0.002	0.008	0.038	0.150	0.331
1.8	0.001	0.002	0.006	0.030	0.119	0.263
2.0	0.001	0.002	0.005	0.024	0.097	0.214
2.5	0.000	0.001	0.003	0.016	0.062	0.138
3.0	0.000	0.001	0.002	0.011	0.043	0.097
3.5	0.000	0.000	0.002	0.008	0.032	0.071
4.0	0.000	0.000	0.001	0.006	0.024	0.055
4.5	0.000	0.000	0.001	0.005	0.019	0.043
5.0	0.000	0.000	0.001	0.004	0.016	0.035
6.0	0.000	0.000	0.001	0.003	0.011	0.024
7.0	0.000	0.000	0.000	0.002	0.008	0.018
8.0	0.000	0.000	0.000	0.002	0.006	0.014
9.0	0.000	0.000	0.000	0.001	0.005	0.011
10.0	0.000	0.000	0.000	0.001	0.004	0.009
11.0	0.000	0.000	0.000	0.001	0.003	0.007
12.0	0.000	0.000	0.000	0.001	0.003	0.006
13.0	0.000	0.000	0.000	0.001	0.002	0.005
14.0	0.000	0.000	0.000	0.000	0.002	0.004
15.0	0.000	0.000	0.000	0.000	0.000	0.004
16.0	0.000	0.000	0.000	0.000	0.002	0.003
17.0	0.000	0.000	0.000	0.000	0.001	0.003
18.0	0.000	0.000	0.000	0.000	0.001	0.003
19.0	0.000	0.000	0.000	0.000	0.001	0.002
20.0	0.000	0.000	0.000	0.000	0.001	0.002
25.0	0.000	0.000	0.000	0.000	0.001	0.001
30.0	0.000	0.000	0.000	0.000	0.000	0.001
35.0	0.000	0.000	0.000	0.000	0.000	0.001
40.0	0.000	0.000	0.000	0.000	0.000	0.001
45.0	0.000	0.000	0.000	0.000	0.000	0.000
50.0	0.000	0.000	0.000	0.000	0.000	0.000
60.0	0.000	0.000	0.000	0.000	0.000	0.000
70.0	0.000	0.000	0.000	0.000	0.000	0.000
80.0	0.000	0.000	0.000	0.000	0.000	0.000
90.0	0.000	0.000	0.000	0.000	0.000	0.000
100.0	0.000	0.000	0.000	0.000	0.000	0.000



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